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RELIABILITY ANALYSIS OF THE EXPERIMENTAL SOLID ROCKET MOTOR OF THE KOSMOS ROCKET DESIGN TEAM

Martin Schultz

Luis Fernando Peres Calil

Joinville's Technological Center (CTJ)/ Federal University of Santa Catarina (UFSC). Rua Dona Francisca, 8300 – Bloco U Zona Industrial Norte Joinville – SC – Brasil - CEP: 89.219-600.

schultzm17@gmail.com

fernando.calil@ufsc.br

Abstract. Due to its complex design and operation in extreme conditions, the rocket motor is one of the most rated items in educational competitions and that most needs attention from the teams. Aiming to analyze the reliability of the high-power experimental solid rocket motor, from the competition team Kosmos Foguetemodelismo at the Joinville's Technological Center of the Federal University of Santa Catarina, the present work sought to list the failure modes, critical components and raise mitigation recommendations for these components. This was accomplished through the Failure Mode and Effect Analysis (FMEA). Thirteen failure modes were identified, eleven causal chains with unacceptable evaluation, twenty-one with undesirable evaluation, fourteen with acceptable if revised and five with acceptable evaluation. The critical components being the grain, the bulkhead screws and the nozzle screws.

Keywords: Competition teams, Experimental Rocket Motor, Reliability, FMEA.

1. INTRODUCTION

Educational competitions are tools that drive development, knowledge, technologies, concepts, creativity and teamwork. They have several approaches, from more conceptual (mathematics, physics) to more technological ones, for example, the SAE (Society of Automotive Engineers) competitions, which include Baja, Formula, Aerodesign and others. Among the competitions of a technological scope, there are also experimental rocket competitions.

Kosmos, a rocket design team from Federal University of Santa Catarina (UFSC), in 2017, has developed their first high power experimental rocket, named Hagemayer 8, that could reach 1000 meters, being able to compete in some competitions. They design from the code behind altitude measurement, to the static fire bench and the Solid Rocket Motor (SRM) as well.

Since the SRM is a critical subsystem for a successful mission and is the most rated item in competitions, it must be designed to be as reliable as possible, as a minimal failure can turn into catastrophic proportions. Therefore, carrying out the study of the reliability of this system becomes necessary.

To analyze the reliability, it started by collecting the necessary information about the Kosmos's SRM, including sizes, materials and characteristics, manufacturing process and their respective functions. Then, the FMEA method was applied, obtaining the critical items, grain and the bulkhead and nozzle screws, and recommendations to improve the reliability of the SRM.

2. METHODOLOGY

The research has the intent to obtain the critical elements of the SRM project and to propose improvements in terms of reliability and safety. To achieve this firstly a study was made of the SRM till the details, then it was chosen the reliability method. That research was made during the SARS-COV-2 pandemic, therefore all the meetings with the FMEA's team were made online, where they wove their opinions about the system and discussed the specific terms of the FMEA processes.

2.1 Experimental SRM

Known as candy rockets, such category of SRM, uses easily obtainable and less dangerous compounds. According to Nakka (2018), in general, potassium nitrate and some kind of sugar, such as sucrose, dextrose, sorbitol, among others, are used to compose the propellant. The SRM of Hagemayer 8 uses potassium nitrate with sorbitol (KNSB) as the propellant. Figure 1 shows the schematic from the SRM.

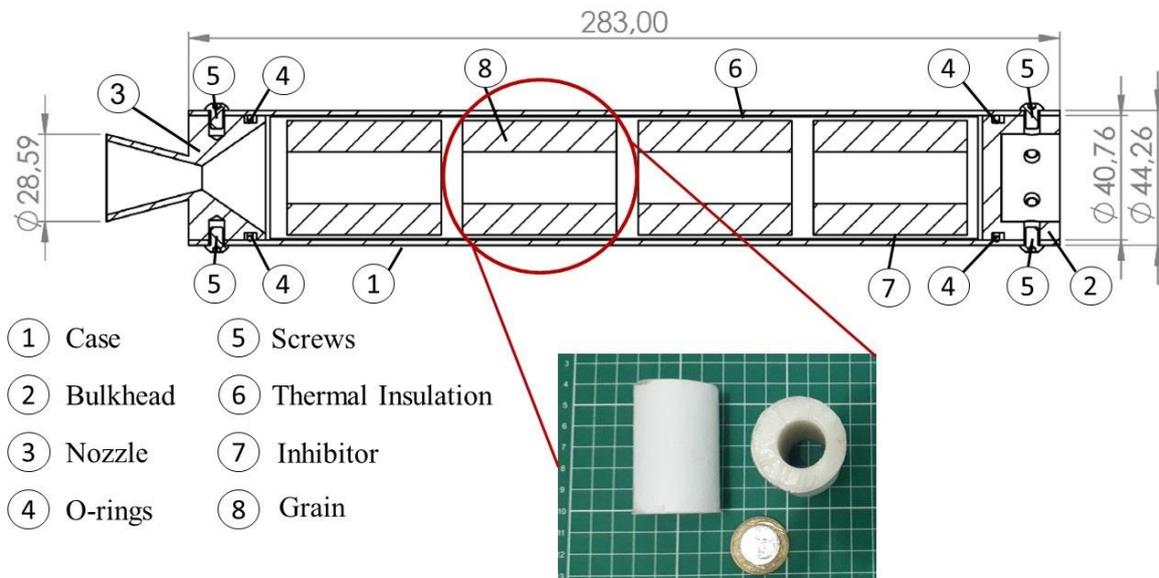


Figure 1. Hagemayer's SRM schematic (measurements in millimeters) with upper and side view from the grains (scale in centimeters).
 Adapted from Schultz (2020).

As described by Schultz (2020), the nozzle and the bulkhead are made of steel AISI 1045 and the case is made of steel AISI 1020. The case and bulkhead are together the combustion chamber of the SRM. There are four solid tubular-shaped segmented grains of KNSB, wrapped by the inhibitor that is made of bond paper with a thin layer of sodium silicate between the grain and the bond paper as highlighted. There is also a thermal insulation (laminated glass-fiber tube), the O-rings and the M6 screws. The Kosmos SRM are an I class, with 380N of average thrust, 6,45MPa internal pressure, with a flame temperature around 1600 K and 1,2 s of operation.

2.2 FMEA

Everdij and Blom (2016) shows in their study that the FMEA is a method used to identify the critical items and is applied in the aerospace and defense industry. Many authors take FMEA and FMECA as different, but to this work, there will be no such distinction.

According to Dias et. al (2011), informs that there is some ways to execute the FMEA, however, in general, recommends the following approach:

- Definition of the system;
- Definition of the team;
- Function Analysis;
- Identifying the failure modes and its effects;
- Identifying the causes and controls;
- Risk assessment;
- Recommendations.

The system to analyze is already chosen, the Kosmos Hagemayer 8 SRM.

2.2.1 Definition of the team

This step consists in obtaining a group of specialists about the system to be analyzed, keeping in mind the multidisciplinary characteristics in each expertise. This step is important to acquire the maximum of plural knowledge, taking their different points of view about the system.

The team was defined with a a specialist in industrial rocket motors, aerospace engineer by UFSC, master in space technologies and sciences by the Instituto Tecnológico da Aeronáutica (ITA), who during the period of this work worked in a company of satellite thrusters in Portugal; a specialist in experimental rocket motors, mechanical engineer from the State University of Rio de Janeiro (UERJ), taking a master's degree in space technology engineering in the field of combustion and propulsion by the National Institute of Space Research (INPE), who won prizes in experimental rocket competitions at national and international level; the Kosmos SRM designer, studying aerospace engineering at UFSC,

responsible for the team's propulsion sector during the Kosmos Hagemayer 8 project; a specialist in manufacturing, production engineer from the State University of Santa Catarina (UDESC), taking a master's degree in engineering and materials science from UFSC and technician at the CTJ machining laboratory; a specialist in materials, professor at UFSC, graduated in physics from UFSC, master in materials engineering from UFSC, doctor in plasma physics from ITA, with post-doctorate in aerospace engineering from the University of Taubaté (UNITAU); a member of another experimental rocket competition team, partner to the Kosmos team, from the propulsion sector, studying mechanical engineering at the Federal University of Rio de Janeiro (UFRJ).

2.2.2 Function Analysis

In order to apply the FMEA method, according to Samatis (2003) it is necessary to define the functions of the system. This step is important to brainstorm the failure modes, coming from the idea that a failure is a non-complying of the function, partially or completely.

The functional analysis followed the method introduced from Dias et. al (2011), which enables us to observe the existing relationship between functions, components, subsystems and environment. According to Carlson (2012), the more accurate the description of the function, the better the understanding of the system and the easier it will be to identify the failure modes, as well as their effects, causes and controls.

2.2.3 Identifying the failure modes, effects, controls and causes

Functions defined, the team will brainstorm the failure modes of each function, their respective effects, in terms of locally, in the surrounding region and in the rocket itself, according to Dias et. al (2011). After that, are raised the controls, which are the barriers that have already been applied in the manufacturing process (DYADEM, 2003). And last, are listed the root causes of the failures.

2.2.4 Risk assessment (R. A.)

In order to obtain the critical items, it is used a risk assessment method, this step helps to rank up all the causal chains. Dias et al. (2011) brings a risk matrix assessment combining the wider spectrum of scenarios from SAE J1739 (2002) with the Risk Assessment Matrix from MIL-STD-882E (2012). The authors define four matrices, composed of, now, risk assessment indicators: severity (S), occurrence (O) and detection difficulty (D). With each matrix based on detection difficulty, from easy (D=1) to very difficult (D=4), with severity versus occurrence, as shown in Figure 3. The authors also recommend scales for severity, occurrence and detection difficulty, as shown in Figure 4.

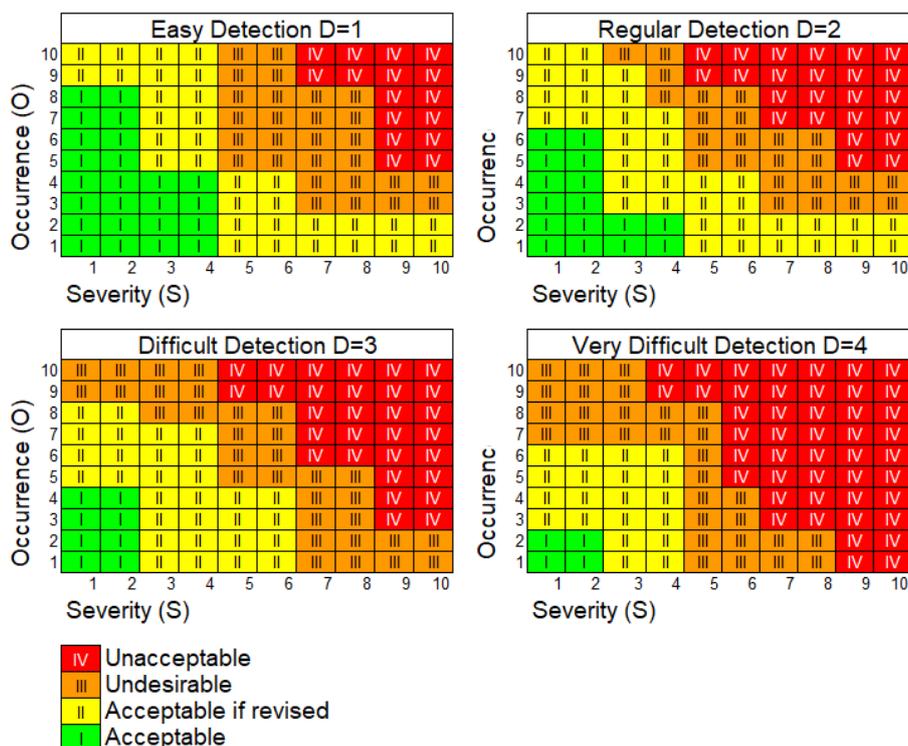


Figure 3. Risk matrix assessment.

Adapted from Dias et al. (2011).

Severity (S)		Occurrence (O)		Detection (D)	
Rate	Description	Rate	Description	Rate	Description
1-2	Insignificant	1-2	Unlikely	1	Easy
3-4	Lower	3-4	Remote	2	Regular
5-6	Greater	5-6	Casual	3	Difficult
7-8	Dangerous	7-8	Likely	4	Very difficult
9-10	Catastrophic	9-10	Often		

Figure 4. Scale for the risk matrix.
 Adapted from Dias et al. (2011).

3. RESULTS

As the first step of the FMEA application process, the Functional Analysis was performed, raising all the MFPS items and their respective functions and the SRM function itself, as shown at Table 1.

Item	Functions
SRM	Provide a projected thrust curve to the rocket; Have elements that allow reconditioning and reuse; Transfer the thrust to the rocket.
Case (#1, Figure 1)	Contain the combustion with the structure itself, to generate the flow in the nozzle; Ensure structural rigidity to the SRM; Fit to bulkhead and nozzle by coupling; Protect the internal parts with the structure itself, from interference from the external environment.
Bulkhead (#2, Figure 1)	Cover the front of the SRM with the structure itself, it to the Case by coupling; Contain the combustion to generate nozzle flow; Serve as a seat for the O-ring.
Nozzle (#3, Figure 1)	Accelerate the heat gases; Serve as a seat for the O-ring; Fit to the Case by coupling; Produce a <i>quasi</i> 1-D flow.
Bulkhead's screws (#5, Figure 1)	Attach the bulkhead to the Case and to the rocket fuselage; Prevent the longitudinal displacement of the bulkhead in relation to the Case, supporting the shear stresses due to the operation; Transmit the thrust to the rocket fuselage.
Nozzle screws (#5, Figure 1)	Attach the nozzle to the Case and to the rocket fuselage; Prevent the longitudinal displacement of the nozzle in relation to the case, supporting the shear stresses due to the operation; Break up to design shear stress; Transmit the thrust to the rocket fuselage.
O-ring (#4, Figure 1)	Seal the bulkhead and nozzle interfaces with the Case, at operating pressure and flame temperature.
Thermal insulation (#6, Figure 1)	Have a low thermal conductivity, preventing the case from reaching critical temperatures.
Inhibitor (#7, Figure 1)	Wrap the grain externally, preventing burning in this region; Generate spacing between grains.
Grain (#8, Figure 1)	Generate combustion gases at a projected burn rate.

Table 1. SRM Functional Analysis.

Knowing the main functions of the SRM and its elements, the team executed brainstorm meetings, where it was listed, discussed and reviewed the failure modes of the SRM, their effects, causes, risk assessments and recommendations. Also was raised the controls (barriers of these causal chains) that were already implemented by Kosmos.

3.1 Combustion chamber FMEA

Table 2 shows the causal chains of the case, risk assessment and recommendations. The controls adopted by Kosmos are: visual inspections on the surface of the thermal insulation, acquisition of certified screws and visual inspection with a crack-revealing paint. The recommendations from the team were to determine the useful life of the material due its operational cycles, do an X-ray test in the acquisition to look for any cracks, do an ultrasound test after each use also looking for any cracks and inspect the roughness in coupling region.

Failure Mode	Effects	Causes	R. A.	Recommendations
Heat gas leaking through the Case body.	<ul style="list-style-type: none"> Leakage of heat gases in the case body; Case overheating in the leakage region; Breakage of the case; Overheating of the fuselage in the leakage region; Fuselage breakage; Explosion; Mission failed. 	Hole or tear in thermal insulation	III	<ul style="list-style-type: none"> Determine the useful life of the material X-ray test in the acquisition Ultrasound test after each use
		No-shear nozzle screws	II	
		Crack in the case body	III	

Table 2. Case's FMEA sheet.

Table 3 shows the causal chain of the bulkhead, risk assessment and recommendations. The control adopted is a visual inspection with a crack-revealing paint. Despite the bulkhead having different cause and effects compared to the case, the failure mode and the recommendations remain the same.

Failure Mode	Effects	Causes	R. A.	Recommendations
Heat gas leaking through the Bulkhead body	<ul style="list-style-type: none"> Overheating of the leak region; bulkhead breakage; Overheating of the fuselage in the leakage region; Fuselage breakage; Separation of fuselage sections; Structural damage to the recovery subsystem; Low thrust; Change in the shape of the thrust curve; Explosion; Mission failed. 	Bulkhead cracked	III	<ul style="list-style-type: none"> Determine the useful life of the material X-ray test in the acquisition Ultrasound test after each use

Table 3. Bulkhead FMEA sheet.

3.2 O-rings FMEA

Table 4 shows the causal chains of the nozzle O-rings, risk assessment and recommendations. The controls adopted are: visual inspection of the O-ring before the insertion, visual inspection of the O-ring gap, lubricate the region of insertion, visual inspection of the roughness of the region, replacement of damaged O-rings and noting a leakage of heat gases. The team's recommendations were to use O-ring redundancy, execution of hydrostatic test to certify the sealing and inspect the roughness in coupling region to prevent any O-ring damage during the insertion.

Failure Mode	Effects	Causes	R. A.	Recommendations
Heat gas leaking through the	<ul style="list-style-type: none"> Overheating in the region of the leak; Loss of internal pressure; 	Displacement of the O-ring out of the gap	III	<ul style="list-style-type: none"> Surface roughness standard inspection O-ring redundancy
		High roughness of the O-ring gap	III	

Case- Nozzle coupling	<ul style="list-style-type: none"> ● Low thrust; ● Change the shape of the thrust curve; ● Change of trajectory; ● Mission failed. 	O-ring damaged	III	- Execution of hydrostatic test
		Breakage of an O-ring by internal pressure	II	
		Adjustment with too large clearance	III	

Table 4. Nozzle O-rings FEMA sheet.

Table 5 shows the causal chains of the bulkhead’s O-rings. As it can be seen, the causal chains from the bulkhead’s O-ring are quite similar to the nozzle O-ring, with different effects. However, the controls and recommendations remain the same.

Failure Mode	Effects	Causes	R. A.	Recommendations
Heat gas leaking through the Case-Bulkhead coupling	<ul style="list-style-type: none"> ● Overheating of the leak region; ● Overheating of the fuselage in the leakage region; ● Fuselage breakage; ● Structural damage to the recovery subsystem; ● Low thrust; ● Change the shape of the thrust curve; ● Mission failed. 	Displacement of the O-ring out of the gap	III	- Surface roughness standard inspection - O-ring redundancy - Execution of hydrostatic test
		O-ring damaged	III	
		High roughness of the O-ring seat	III	
		Breakage of an O-ring by internal pressure	III	
		Adjustment with very large clearance	III	

Table 5. Bulkhead’s O-rings FEMA sheet.

3.3 Grain FMEA

Table 6 shows the causal chains of the grain, risk assessment and recommendations. The controls adopted are: heating the mold before the pour, correct curing time applied, 1MPa compression, measurements of grain dimensions, visual inspection of the grain, handling the grain with gloves, light lubrication of the mold, calculus of the grain’s specific density, standardized grain fabrication, use of precision scale, correct ignitor positioning, grain storage in silica gel, minimum time exposing to the atmosphere. Team’s recommendations were a use of non-aggressive ignitors, preventing some grain damage during the ignition phase; to remove the mold core with a press to keep a constant pressure, avoiding damage to the grain during this process; use a sieve to guarantee the propellants compounds designed granulometry; vacuum compression and curing of the grain to prevent bubbles inside the grain; do X-ray test to verify internal cracks and bubbles. The grain was the item that most received high and low risk assessments, related to the variation in its burning rate: when higher, high risk, when lower, low risk.

Failure Mode	Effects	Causes	R. A.	Recommendations
Grain burning rate higher than designed	<ul style="list-style-type: none"> ● Excessive gas generation; ● Breakage of the grain; ● Decrease in burning time; ● Dilation of the case above the specified; ● Expansion of the bulkhead above specified; ● Clogging of the nozzle; 	Non-homogeneous curing of the grain	IV	- Vacuum compression and curing of the grain - Non-aggressive ignitors - Remove the mold core with a press - X-ray test - Apply vibration on the mold
		High speed of material loss due to erosive grain burning	III	
		Grain burning surface area greater than the design	III	
		Cracked grain	IV	

	<ul style="list-style-type: none"> ● Excessive pressure on screws; ● Excessive pressure on seals; ● Excessive pressure in the fuselage; ● Excessive pressure on the recovery subsystem; ● Change in the shape of the thrust curve; ● Explosion; ● Mission failed 	Bubbles in the grain	IV	- Use of a sieve
		Particle size smaller than the design	IV	
		Burning in an inhibited region	II	
		Incorrect proportions and mixture of propellant compounds	II	
Grain burning rate lower than designed	<ul style="list-style-type: none"> ● Insufficient gas generation; ● Increased burning time; ● Pressure reduction; ● No pressurization; ● Prolonged exposure of internal elements to flame temperatures; ● Low thrust; ● Change in the shape of the thrust curve; ● Mission failed 	Presence of moisture in the grain	II	- Vacuum compression and curing of the grain - Use of a sieve
		Grain burning surface area smaller than the design	I	
		Grain size greater than design	II	
		Incorrect proportions and mixture of inputs	I	
No burning rate	<ul style="list-style-type: none"> ● No gas generation; ● Mission aborted. 	Wet grain	I	- Adopting an ignition system with health monitoring system
		Non-ignition of the grain	I	

Table 6. Grain FEMA sheet

3.4 Nozzle FMEA

Table 7 shows the causal chains of the nozzle, risk assessment and recommendations. The controls are: visual inspection, dimensions measurements after fabrication and after each use, assemble inspection, nozzle cross bolting. Team's recommendations were to implement a pass-no-pass template to ensure the coaxial nozzle; adopting a smoother geometry at the nozzle throat to prevent flow separation due the sudden geometry variation; adopting tapered fitting design to guarantee the concentric coupling with the case; inspect the roughness in coupling region and internal nozzle surfaces.

Failure Mode	Effects	Causes	R. A.	Recommendations
Under-expansion gases	<ul style="list-style-type: none"> ● Detachment of gas flow on the wall of the nozzle; ● Regressive grain burning; ● Increased internal pressure; ● Low thrust; ● Change in the shape of the thrust curve; ● Mission failed. 	Clogged nozzle	II	- Pass-no-pass template - Smooth geometry at the nozzle - Surface roughness standard inspection - Roughness meter
		Inappropriate divergent-converging geometry	I	
		Nozzle with rough surfaces	II	
Eccentric thrust	<ul style="list-style-type: none"> ● Flow with directions other than projected; ● Compression stress at the end of the case; ● Rocket trajectory changing; ● Mission failed. 	Non-collinear nozzle assembly	III	- Tapered fitting design
		Nozzle geometry out of specification	III	

Table 7. Nozzle FEMA sheet.

3.5 Screws FMEA

Table 8 shows the causal chains of the nozzle screws, risk assessment and recommendations. The controls are: visual inspection during the assemble, cross-check, check the dimensions, hand screws tightening, visual inspection after each use, fixing screws holes. Team’s recommendations were to determine the useful life of the screws; mechanical test to verify the safety factor designed; replacing the crews every use; insert the screws with a torque meter; do an X-ray test in acquisition.

Failure Mode	Effects	Causes	R. A.	Recommendations
One or more Nozzle screws missing	<ul style="list-style-type: none"> • Nozzle not properly attached to motor • Displacement of the nozzle due to internal pressure; • Non-collinear nozzle with the case; • Leakage of heat gases; • Thrust eccentricity; • Motor not properly attached to fuselage; • Impaired thrust transfer; • Mission failed. 	Assembly error	II	
		Hole out of specification	II	
One or more breaking Nozzle screws	<ul style="list-style-type: none"> • Nozzle ejection due to internal pressure; • Non-contained and non-accelerated combustion gases; • Nozzle not attached to the fuselage; • Structural damage to the fuselage; • Low thrust; • Change in the shape of the thrust curve; • Mission failed. 	Fatigue screws	IV	<ul style="list-style-type: none"> - Certified screws - Determine the useful life of the screws - Replacing the crews every use - X-ray test in acquisition - Torque meter use - Mechanical test
		Crack in screws	IV	
		Insufficient tightening of the screws	III	
		Tightening the screws too much	IV	
		Screws smaller than specification	II	
		Damaged screw	III	
		Internal pressure greater than projected	III	

Table 8. Nozzle screws FEMA sheet.

An apparently contradictory failure mode is the rupture of the nozzle screws, as these must fail, however, only when necessary. For example, when there is a pressure spike inside the motor, the screws break up, relieving the pressure and preventing catastrophic failure.

Table 9 shows the causal chains of the Bulkhead’s screws, risk assessment and recommendations. Controls and team’s recommendations were the same from the nozzle screws, although there are some different causal chains than the nozzle screws.

Failure Mode	Effects	Causes	R. A.	Recommendations
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One or more Bulkhead screws missing	<ul style="list-style-type: none"> ● Bulkhead not properly attached to the motor; ● Displacement of the bulkhead and due to internal pressure; ● Leakage of combustion gases; ● Increased tensions in the other screws of the bulkhead; ● Overheating of the fuselage; ● Structural damage to the fuselage; ● Structural damage to the recovery subsystem; ● Impaired thrust transfer; ● Mission failed. 	Assembly error	II	
		Hole out of specification	II	
One or more breaking Bulkhead screws	<ul style="list-style-type: none"> ● Displacement of the bulkhead; ● bulkhead ejection due to internal pressure; ● Leakage of combustion gases; ● Loss of attachment of the bulkhead to the motor; ● Overheating of the fuselage; ● Structural damage to the fuselage; ● Structural damage to the recovery subsystem; ● Low thrust; ● Change in the shape of the thrust curve; ● Mission failed. 	Crack in screws	IV	<ul style="list-style-type: none"> - Determine the useful life of the screws - X-ray test in acquisition of the screw - Torque meter use - Replacing the crews every use - Mechanical test - Certified screws
		Insufficient tightening of the screws	III	
		Tightening the screws too much	IV	
		No shear of the nozzle screws	IV	
		Screws smaller than specification	II	
		Damaged screw	III	
		Fatigue screws	IV	

Table 9. Bulkhead's screws FMEA sheet.

By applying FMEA, thirteen failure modes were identified and 51 causal chains, as shown in the tables above. Eleven causal chains with Unacceptable (IV) evaluation, twenty-one with Undesirable (III) evaluation, fourteen with Acceptable if Revised (II) and five with Acceptable (I) evaluation. The critical components, which means, those items that received, at least one Unacceptable evaluation, are the grain, the bulkhead's screws and the nozzle's screws.

All Unacceptable risk assessments are between the grain and nozzle and bulkhead's screws, thus suggesting that the reliability of the SRM will increase considerably by adopting the team's recommendations for these components.

Using x-ray and ultrasound serve to identify internal cracks in the structure of items, however they are applied at different times, for different items. The x-ray of the grain is done after it has cured, this process is used to identify cracks and internal bubbles. As for the metallic elements (case, nozzle, screws and bulkhead) the x-ray is used in the acquisition of these components, to identify internal cracks and the ultrasound is used to identify the cracks after each use of the component.

4. FINAL CONSIDERATIONS

It was demonstrated the application of the FMEA method in each component of the SRM. Also were identified the critical components, as desired, and the recommendations to be applied by Kosmos team. Those recommendations will increase the SRM reliability, being able to be considered in future projects.

The team's recommendations are intended to ensure that all risk assessments are acceptable. However, due to the functioning of a solid rocket motor, acceptable levels of risk assessment are not possible, so the concept of "as low as reasonably possible" (ALARP) is used. This does not mean that the reliability analysis of SRM's have no impact, despite not reaching the expected levels of risk assessment, they are still very important tools in the aerospace industry, acting on the quality of the entire production chain.

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